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RESEARCH ARTICLE

Volatile Flavor Fingerprints of 'Monthong' Durian (*Durio zibethinus*) from Four Geographical Indication Regions in Thailand

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Abstract

Monthong durian is the most widely cultivated and commercially important cultivar in Thailand for both domestic consumption and export. Increasing consumer interest has focused on the complex taste and aroma of 'Monthong' produced in different geographical indication (GI) areas; however, comprehensive studies on its quality attributes and volatile compound profiles remain limited. The quality attributes (dry matter content, sulfur content, color, sugars, volatile flavor compounds, and sensory properties) of the fruit from four Thai GI regions (Prachin Buri, Uthai Thani, Rayong, and Pala-U) were investigated. At a uniform harvest maturity of 120 days after anthesis (DAA), durian from Uthai Thani, Pala-U, and Prachin Buri exhibited significantly higher dry matter content than fruit from Rayong. Rayong durian showed the highest sulfur content, which was associated with elevated ethanethiol levels at the ripe stage and a sensory profile characterized by a strong sulfurous odor and reduced fruity aroma. Pulp yellowness did not differ significantly among regions. In all regions, sucrose was the predominant sugar, followed by glucose and fructose. A total of 28 volatile compounds were identified in the durian pulp, including 23 esters, two sulfur-containing compounds, and three alcohols. Ethanethiol was the dominant sulfur compound across all sources. Ethyl 2-methylbutanoate, which exhibited a high odor activity value (OAV) and a low aroma threshold value (ATV), was the major ester contributing to durian aroma. Pala-U durian contained the lowest total ester content and exhibited a mild aroma profile; however, it received favorable sensory evaluations, characterized by fruity notes, reduced sulfurous odor, and a creamy, rich, creaminess, and umami taste. Principal component analysis (PCA) showed that the first two components explained 70.5% of flavor variance, indicating a strong regional effect on durian flavor. These findings support future research on enhancing flavor complexity in 'Monthong' durian from GI regions in Thailand.

Keywords: Monthong durian, Dry matter, Maturity, Sulfur content, Geographical indication, Ester compound, Sulfur-containing compound, Sensory evaluation

Introduction

Durian (*Durio zibethinus* Murr.) is an edible tropical fruit widely cultivated in Southeast Asia. Commonly referred to as the "King of Fruits" due to its rich, sweet, and creamy taste coupled with a strong, distinctive odor, durian holds significant cultural and economic importance in the region [1,2]. According 2024 data, Thailand is the largest producer and exporter, with a planting area of approximately 180,000 to 200,000 ha, followed by Vietnam with around 155,000 ha, and Malaysia with approximately 85,000 to 90,000 ha. Indonesia has a substantial durian planting area, precise data are unavailable, and most of its production is consumed domestically. Recently, Indonesia has launched initiatives to cultivate commercially significant durian varieties, particularly the 'Monthong' cultivar, for export to the Chinese market. Similarly, the Philippines currently has a planting area of about 8,000 to 9,000 ha and is aiming to expand to 50,000 ha to support fresh durian exports to China [3-7].

For the quality of durian is traditionally assessed using physical attributes and maturity indices. Monthong is the most popular durian clone in Thailand for both domestic consumption and export. Following Thailand durian standard, a dry matter content (DM) exceeding 32% is required to confirm harvest maturity according to Thai quality standards [1,6,8]. Dry matter (DM) is strongly associated with starch accumulation in unripe durian; fruits with higher DM typically contain greater starch content in the pulp. During ripening, starch is hydrolyzed into soluble sugars, predominantly sucrose, which can subsequently be converted into reducing sugars such as glucose and fructose [1]. The application of sulfur-containing fertilizers in durian orchards can lead to sulfur accumulation in the pulp, influencing the levels of sulfur-containing amino acids, particularly methionine and ethionine, which serve as precursors for ethanethiol, a key contributor to durian aroma [9]. In addition, sulfur availability affects the formation of 1-aminocyclopropane-1-carboxylic acid (ACC) and ethylene production *via* the Yang cycle. Ethylene functions as a key regulator of volatile biosynthesis during fruit ripening [10]. Ethanethiol is a primary sulfur-containing odorant in durian, especially in 'Monthong', while esters such as ethyl 2-methylbutanoate, ethyl hexanoate, and ethyl octanoate are major contributors to the characteristic fruity aroma profile of this cultivar [11].

Nevertheless, considerable variability in eating quality persists among fruits meeting this threshold, highlighting the need for a deeper understanding of flavor-related chemical attributes. Consumer demand for premium 'Monthong' durian increasingly prioritizes complex sensory characteristics, particularly a deep, rich, fruity, and full-bodied flavor without sulfur-related off-odors. Geographical indication (GI) durian is recognized for its distinctive sensory identity, suggesting a strong link between production origin and flavor chemistry. Fruit flavor is determined by the composition and interactions of volatile compounds, which are influenced by preharvest factors such as soil composition, nutrition, climate, irrigation, and orchard management [12-17]. Advances in OMICS-based approaches, particularly metabolomics, have provided powerful tools for characterizing flavor-active compounds and their biosynthetic origins e.g., fatty acid content [18]. However, limited information is available on how GI-related preharvest factors contribute to the volatile profiles of 'Monthong' durian. Although the quality attributes and volatile composition of 'Monthong' durian have been extensively studied, most research has focused on fruit sourced from commercial export production areas, particularly Chanthaburi Province [11,19-23]. In contrast, 'Monthong' durian from geographical indication (GI) areas has attracted increasing interest due to its more complex aroma and flavor profile, as well as its higher market value compared to fruit from conventional production areas. Currently, Thailand has 19 registered GI durian production areas encompassing various cultivars. In this study, we focused on 'Monthong' durian from four selected regions: Rayong (a GI area and major commercial export production region), Prachin Buri, Pala-U, and Uthai Thani (an emerging production area currently undergoing GI registration) [24,25].

Therefore, this study investigates high-quality GI 'Monthong' durian from different production regions in Thailand to elucidate key volatile compounds and eating quality attributes associated with premium flavor beyond conventional maturity criteria. This study also investigated volatile compounds in relation to sensory perception, using highly experienced assessors familiar with 'Monthong' durian from GI areas across Thailand

to evaluate flavor complexity in comparison with quality attributes and volatile profiles. The findings provide a foundation for future research aimed at producing high-quality 'Monthong' durian with enhanced flavor complexity in GI regions of Thailand.

Materials and methods

Durian preparation

High-quality 'Monthong' durian fruits were selected from four production areas in Thailand. The first source was Prachin Buri, one of Thailand's registered geographical indication (GI) regions for Monthong durian, characterized by thick pulp with an intense yellow color and a sweet, oily taste. The second source was Rayong, also a GI region, where the pulp is characterized by a thick aril, smooth yellow color, high dry matter content, low fiber, distinct aroma, and a sweet, oily taste. The third source was Pala-U in Prachuap Khiri Khan Province, where the pulp exhibits a thick aril, light yellow color, high dry matter content, low aroma, and a sweet, oily taste. The fourth source was Uthai Thani, a newly established production area currently in the process of registration as a novel GI region. Durian from this source is characterized by high pulp dry matter content, low odor and fiber content, and a sweet, oily taste (**Table 1**). All durian fruits were harvested at 120 days after anthesis (DAA) and transported to the laboratory for analysis within 24 h. Three durian fruits (2.5 - 3.0 kg per fruit) were sampled from a selected orchard in each study area. Only fruits from healthy trees exhibiting normal leaf development and no visible abnormalities were included in the study. The characteristics of the cultivation areas, including soil properties, fertilizer application practices, and irrigation management, varied among the study sites and are presented in **Table 1**.

Table 1 Characteristic attributes of climate, soil profile, durian traits, and seasonality in geographical indication areas of 'Monthong' durian.

Character attributes	**Prachin Buri** [24]	**Uthai Thani** [25]	**Rayong** [24]	**Pala-U** [24]
Climatic characteristic	The climate is classified as tropical, located near the equatorial zone. During the summer season, the weather is extremely hot, influenced by the southwest monsoon. In contrast, the winter season is relatively cool due to the influence of the northeast monsoon.	The climate is classified as tropical semi-humid to humid. The area is predominantly mountainous and covered with dense, fertile forests, resulting in a generally cool and comfortable environment throughout the year, particularly during the early morning and nighttime periods.	The region experiences a tropical monsoon climate, influenced by sea breezes throughout the year. The weather is generally warm without extreme heat, with abundant rainfall occurring from May to October.	High relative humidity and lower temperature at night
Soil profile	Sandy loam in the upper layer, while the subsoil consists of rock and laterite	Sandy loam or moderately deep soil, often containing gravel in the subsoil layer.	Sandy loam	Sandy loam
Durian character	The flesh is large and finely textured, with a dry consistency and a	The flavor is rich, sweet, and creamy, with a smooth, non-watery	The rind is thin, with clearly defined segments. The flesh is	The flesh is thick and dense, with a pale-yellow color

Character attributes	Prachin Buri [24]	Uthai Thani [25]	Rayong [24]	Pala-U [24]
following GI description	deep yellow coloration. It exhibits a rich, sweet, and creamy flavor.	texture and a mild, non-pungent aroma.	thick and finely textured, exhibiting a pale-yellow color with a dry, slightly sticky consistency and low fiber content. It has a mild, pleasant aroma and a rich, sweet, and creamy flavor.	and a dry, smooth, and fine texture. It exhibits a mild aroma and a rich, sweet, and creamy flavor. The seed is small and underdeveloped.
Seasonality	May - July	July - August	April - June	May - August
Fertilizers after full bloom*	15-5-20 15-5-25 (+7% sulfate) 0-0-30 (K_2O)-after 90 DAA	15-5-20 15-5-25 (+7% sulfate) every 10 day and stop using at 100 DAA (before harvesting 20 d)	0-0-60 KCl 200 g/200 L water every 2 day after that 16-16-16 and 15-5-20 and 15-5-25 (+7% sulfate) with 400 g every 10 day per tree and spray with amino acid at leaf every 10 day	No fertilizer application
Irrigation	Irrigation was applied for 20 min every two days throughout fruit development and withheld for 3 - 6 days before harvest. Actual irrigation requirements may have varied among regions depending on rainfall and local environmental conditions.			

*Fertilization Practices of Selected Orchards in the Geographical Indication (GI) Regions.

Determination of dry matter in unripe durian pulp

The dry matter (DM) content of durian pulp was determined according to the Thai Durian Standard [8]. Freshly harvested unripe durians were cross-sectioned, and 20 g of pulp was collected from the outer portion of the aril around the fruit. The fresh weight was recorded, and the sample was then dried in a hot-air oven at 70 °C for 48 h. After drying, the dry weight was measured, and the percentage of dry matter was calculated using Eq. (1). According to the Thai Durian Standard, the DM content of Monthong durian must exceed 32%. If the value is below this threshold, the fruit is classified as immature.

$$\%DM = (\text{Fresh weight})/(\text{Dry weight}) \times 100 \quad (1)$$

Measurement of sulfur content in unripe durian pulp

Unripe durian pulp samples from dry matter in unripe durian pulp were dried at 90 °C for 2 h to ensure complete dehydration. The sulfur content of the pulp was determined in accordance with ASTM D4239 using a CHNS analyzer (628 Series, LECO Corporation, USA). The analysis began by weighing the sample into a combustion boat, which was then introduced into a furnace supplied with pure oxygen at 1,350 °C. Sulfur present in the sample was released during combustion and oxidized to form SO_2. The combustion gases exiting the furnace were initially swept past the boat stop to the rear of the inner combustion tube and then directed forward between the inner and outer combustion tubes. This flow path prolonged the residence time of the gases within the high-temperature zone, thereby promoting

efficient oxidation. The gases subsequently passed through an anhydrone tube to remove moisture, followed by a flow controller that regulated the gas stream entering the sulfur infrared detection cell of the instrument. A certified reference coal material (Alpha Resources LLC, USA) was used as the standard. The combustion furnace temperature was raised to 1,350 °C. Sulfur content was calculated and expressed as a percentage by weight on a dry matter basis (% w/w DM).

Color determination of durian pulp

Pulp color was measured using a spectrophotometer (MiniScan EZ, Hunter Associates Laboratory, USA) equipped with a D65 illuminant and a 10° observation angle. Color was evaluated according to the Hunter color system following [23], including L* (lightness), a*(+a* indicates redness, –a* indicates greenness), and b*(+b* indicates yellowness, –b* indicates blueness). Chroma (C*) was calculated as [a^{*2} + b^{*2}]$^{1/2}$), and the hue angle ($h°$) was determined as $\tan^{-1}$(b*/a*)). The total color difference (TCD, ΔE) was calculated using Eq. (2).

$$TCD \text{ or } \Delta E = \sqrt{\Delta a^{*2} + \Delta b^{*2} + \Delta L^{*2}} \quad (2)$$

Sugar content determination

The extraction method followed [23]. Durian pulp (4 g) was blended with 12 mL of distilled water and thoroughly homogenized. The homogenate sample was centrifuged at 12,000×g for 25 min and subsequently filtered through a 0.45 membrane filter. Sugar determination was carried out using high-performance liquid chromatography (HPLC) (Shimadzu, Japan) equipped with an NH2 column and a reflective index (RI) detector. The injection volume of filtrated sample was 20 µL. The mobile phase was water (HPLC grade) and acetonitrile with (80:20, v/v), and the flow rate was maintained at 1.0 mL·min^{-1}. Individual sugars were identified and quantified using the external standards of glucose, fructose, (Sigma-Aldrich, USA) and sucrose (Merck, Germany).

Quantitative analysis in volatile compounds of durian pulp

Volatile compounds in 'Monthong' durian pulp were determined using a modified method based on the procedure described by [26]. After opening the package, durian pulp (without seed) was immediately transferred to a freezer at −30 °C. A 10 g portion of pulp from the same fruit was quickly placed into a 20 mL vial and stored at −30 °C until analysis. For solid-phase microextraction (SPME), a 50/30 µm DVB/CAR/PDMS (Divinylbenzene/Carboxen/Polydimethylsiloxane) Stable-Flex^{TM} fiber (57348-U, Supelco, Bellefonte, PA, USA) was conditioned at 240 °C for 5 min in the heater port of the CombiPAL system prior to analysis. For sample preparation, 1 mL of a saturated solution of NaCl solution and a freshly prepared internal standard were added to each sample vial. Specifically, 10 µL of a 5 µL·mL^{-1} thiophene solution in ethanol was spiked into the vial as the internal standard. The vials were then adsorbed in the heating chamber at 50 °C for 10 min with continuous agitation at 500 rpm (5 s on, 2 s off) to facilitate headspace extraction.

Gas chromatographic analysis was conducted using an Agilent 7890B gas chromatograph coupled with a 5977A mass spectrometer (Agilent Technologies, USA). Following extraction, the SPME fiber was immediately inserted into the GC injection port at 240 °C in splitless mode using a Merlin septum, and held for 5 min. Volatile compounds were separated on an HP-5MS capillary column using the following temperature program: The oven was initially set at 40 °C and held for 2 min, then increased to 150 °C at a rate of 5 °C·min^{-1}, followed by a ramp to 250 °C at 30 °C·min^{-1} and held for 5 min. High-purity helium was used as the carrier gas at a constant flow rate of 1.0 mL·min^{-1}.

The mass spectrometer was operated in scan mode over an m/z range of 25 - 500 at a scan rate of 3.1 scans·s^{-1}, using electron ionization (EI) at 70 eV. The ion source temperature was maintained at 230 °C, and the quadrupole temperature was set at 150 °C. Data acquisition was performed using MassHunter software (Agilent Technologies). Compound identification was achieved by matching mass spectra matching with the NIST and Wiley libraries, with a similarity threshold greater than 90%. Identification was further confirmed by comparing GC retention times and retention indices

(RIs), which were calculated using a homologous series of n-alkanes (C_8–C_{22}). The semi-quantitative analysis, concentrations of volatile compounds were expressed as the equivalent of the internal standard (thiophene). Results were reported as micrograms of thiophene equivalents per gram of fresh weight (μg thiophene eq·g^{-1} FW).

Sensory evaluation

Based on our previous study, the eating quality of 'Monthong' durian varies considerably as a result of both preharvest and postharvest factors. In commercial production, 'Monthong' fruit is produced in accordance with Thai quality standards and generally meets all regulatory requirements. Most commercially produced fruit exhibits a high intensity of aroma compounds, particularly esters and sulfur-containing compounds, resulting in a strong ester-like and sulfurous flavor profile. Therefore, sensory evaluation of 'Monthong' durian from geographical indication areas was conducted by experienced assessors. Five healthy panelists (3 males and 2 females) with extensive experience in evaluating 'Monthong' durian pulp from all major production regions in Thailand participated in this study. These panelists were selected for their ability to discriminate subtle differences in taste, flavor intensity, and characteristic flavor notes of geographical indication areas 'Monthong' durian pulp. The panelists evaluated the samples using a 9-point hedonic scale with randomized sample presentation. Quantitative descriptive analysis (QDA) was also conducted based on a consensus list of five sensory descriptors: appearance, fruity aroma, sulfur-like aroma, creaminess, and umami taste. Thus, the sensory evaluation was conducted using professional panelists. Nevertheless, no formal permission was taken for this study but we conducted it adhering to the required guidelines for safeguarding the rights and privacy of all participants. Additionally, the input from these participants was utilized in this study with their consent.

Statistical analysis

All experiments were conducted using a randomized complete design (RCD) with three replicates, with one fruit considered as an experimental unit (replicate). Data were subjected to analysis of variance (ANOVA), and mean comparisons were performed using Duncan's Multiple Range Test (DMRT). Statistical analyses were conducted using SAS University Edition OnDemand for Academics, with significance determined at $p \leq 0.05$. Principal component analysis (PCA), k-means clustering, and heatmap visualization were performed using MetaboAnalyst version 6.0 (https://www.metaboanalyst.ca/). These multivariate analyses were conducted using selected durian quality attributes, including key volatile compounds, sensory evaluation scores, and sugar composition data.

Results and discussion

Postharvest handling Monthong durian

Figure 1 illustrates postharvest handling techniques for 'Monthong' durian in the packing house after harvest, including quality selection procedures. The same flowchart also depicts the classification of fruit quality. After harvest, fruits with DM content higher than 32%, in accordance with national standards [8], are evaluated for further processing. Fruits with DM values of approximately 32% - 34% are typically processed for export, whereas fruits with lower DM are classified as immature durian. In contrast, fruits with very high DM are considered nearly fully matured and are generally unsuitable for export due to their shorter shelf life. In some cases, for fruit approaching full maturity intended for export, ethylene inhibitors such as 1-methylcyclopropene (1-MCP) may be applied to prolong shelf life. Conversely, ethylene-releasing agents, such as ethephon, may be used in exported produce to accelerate ripening and promote uniform ripening throughout the fruit [1]. For 'deep-taste', complex aroma in durian fruits with DM values greater than 35% and lower sulfur content in the pulp dry matter are selected. Under standard conditions, sulfur content in durian pulp is approximately 0.1% (dry weight) [27]. Sulfur in the pulp serves as a precursor for sulfur-containing amino acids, such as methionine and ethionine, which are involved in ethylene biosynthesis *via* the Yang's cycle. These amino acids are also transformed into thiol and disulfide compounds during ripening. Therefore, when pulp sulfur content exceeds 0.1%, particularly in combination with ethephon-induced ethylene production, sulfur is increasingly converted into thiols (e.g., methanethiol and ethanethiol) and further oxidized into sulfides such as

diethyl disulfide and diethyl trisulfide [9,15]. These processes result in ripe fruit with intense sulfur odors, contributing to undesirable off-odors in 'Monthong' durian and reduced consumer acceptance. In contrast, fruits with high DM (indicating high carbohydrate content) and lower sulfur levels (<0.1% dry weight) produce fewer sulfur-containing compounds during ripening, resulting in a milder aroma profile with reduced sulfur odor.

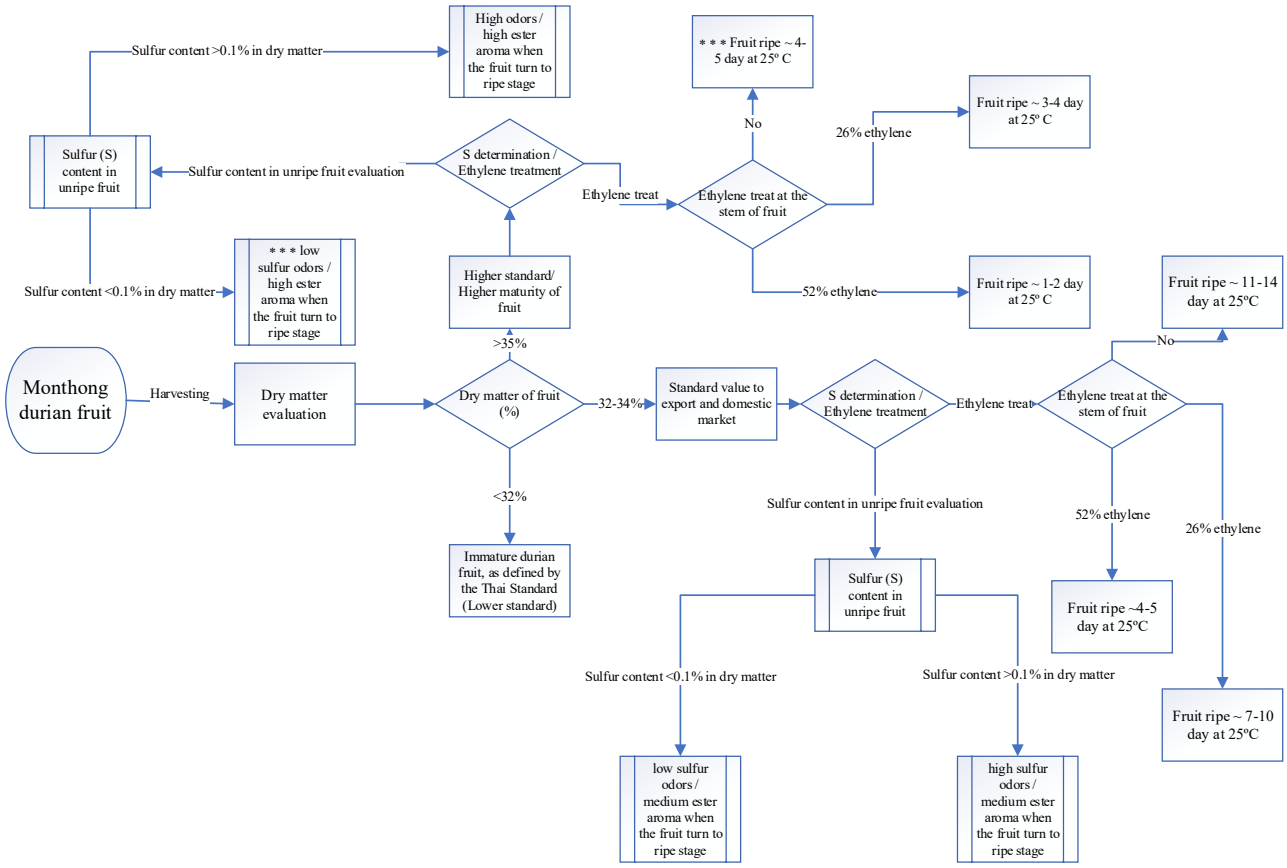


Figure 1 The durian selection process in accordance with export standards, including guidance for selecting premium Monthong durian with complex taste.

Unripe and ripe durian characteristics

Seed coat color has been disseminated as an indicator of fruit maturity, particularly in Thailand's online durian market, where maturity is often discussed based on visual assessment of seed coat color. Consumers commonly perceive fruits with a light brown seed coat as immature. Typically, durian seeds are hard and covered with a thin, light brown testa, which gradually darkens as the fruit reaches maturity [1]. However, the relationship between seed coat color at the mature-but-unripe stage has not been well elucidated. In this study, **Figure 2** illustrates the seed coat characteristics of 'Monthong' durian at a maturity level of approximately 44% - 48% DM, indicating fruit that is nearly fully matured but still unripe. At this stage, the seed coat exhibits a lighter color, which darkens as the fruit progresses to the ripe stage. Notably, at full ovule and endosperm development, the inner layer of the seed coat becomes clearly differentiated from the outer layer, indicating advanced seed maturity.



(A) (B)

Figure 2 Seeds at the unripe stage (A) and ripe stage (B) of 'Monthong' durian maturity (dry matter 44% - 48%).

Quantitative color analysis showed that the redness (a^*) of the outer seed coat in ripe pulp was significantly higher than that in unripe pulp (19.12 ± 1.32, and 7.65 ± 1.25, respectively). The total color difference (TCD, ΔE) between unripe and ripe stages was approximately 27.62 ± 1.47, exceeding the perceptibility threshold of 5 and confirming that the color change is clearly detectable by the naked eye [28]. Similar trends were observed in pulp color. Both redness (a^*) and yellowness (b^*) of the pulp differed significantly between unripe and ripe stages, with values of 2.32 ± 0.43 and 39.95 ± 3.09 in ripe pulp compared with 1.04 ± 0.31 and 33.43 ± 0.68 in unripe pulp, respectively. The TCD value for pulp color change was approximately 8.02 ± 3.05, indicating that the color transition during ripening is also visually detectable (**Table 1** and **Figure 3**).

Regarding sugar composition, durian pulp contains three major sugars—fructose, glucose, and sucrose—with sucrose as the predominant non-reducing sugar. Sucrose is composed of the reducing sugars fructose and glucose. In unripe pulp, fructose was not detected; however, upon ripening, fructose content increased to 24.35 ± 3.16 $g \cdot kg^{-1}$. Both sucrose and glucose contents increased markedly from unripe to ripe stages, rising from 58.09 ± 2.01 $g \cdot kg^{-1}$ to 154.56 ± 11.61 $g \cdot kg^{-1}$ for sucrose and from 18.13 ± 2.01 $g \cdot kg^{-1}$ to 117.02 ± 6.48 $g \cdot kg^{-1}$ for glucose. These results indicate that carbohydrate-to-sugar conversion begins prior to harvest and continues during ripening (**Table 2**) [1].



(A) (B) (C) (D)

Figure 3 Various sources of 'Monthong' durian plants from Prachin Buri (A), Uthai Thani (B), Rayong (C), and Pala-U (D).

Table 2 Color parameters and total color difference (TCD, ΔE) in unripe and ripe stages of 'Monthong' durian pulp.

Attributes	Treatment	
	Unripe stage	**Ripe stage**
Durian seed		
L^*	$80.49^a \pm 3.03$	$55.57^b \pm 1.61$
a^*	$7.65^b \pm 1.25$	$19.12^a \pm 1.32$
$b^{*\,ns}$	31.70 ± 3.31	34.50 ± 1.18
C^*	$32.61^b \pm 3.48$	$39.45^a \pm 1.67$
h	$76.51^a \pm 1.14$	$61.07^b \pm 0.87$
ΔE		27.62 ± 1.47
Durian pulp		
L^*	$85.40^a \pm 0.33$	$81.01^b \pm 0.92$
a^*	$1.04^b \pm 0.31$	$2.32^a \pm 0.43$
b^*	$33.43^b \pm 0.68$	$39.95^a \pm 3.09$
C^*	$33.44^b \pm 0.69$	$40.02^a \pm 3.11$
h	$88.27^a \pm 0.50$	$86.74^b \pm 0.40$
ΔE		8.02 ± 3.05
Fructose (g kg^{-1})	N.D.	24.35 ± 3.16
Glucose (g kg^{-1})	$18.13^b \pm 2.01$	$117.02^a \pm 6.48$
Sucrose (g kg^{-1})	$58.09^b \pm 2.01$	$154.56^a \pm 11.61$

Data are expressed as the mean values ± SD of three replicate assays, N.D. is not detected.

^{a,b} letters indicate significant different ($p \leq 0.05$) values according to the Duncan's multiple range test (DMRT) in the same row, ns is no significant difference.

Sulfur content, color and sugars in unripe durian various sources

Dry matter (DM, %), sulfur content (%), pulp color, sugar composition, and descriptive sensory attributes evaluated by experienced 'Monthong' durian assessors were compared among four selected production areas: Prachin Buri, Uthai Thani, Rayong, and Pala-U (**Table 3**). All 'Monthong' durians were harvested at the same physiological stage, 120 days after anthesis (DAA). The results indicated that the selected fruits exhibited a high level of maturity, with DM values exceeding 34% in this study. Sulfur content was determined in a pulp dry matter basis for all samples. Despite the identical DAA, 'Monthong' durian from Uthai Thani exhibited the highest DM, followed by those from Prachin Buri and Pala-U, while Rayong exhibited the lowest DM. Nevertheless, no significant differences in DM were observed among the three geographical indication (GI) areas—Prachin Buri, Uthai Thani, and Pala-U—whereas Rayong remained significantly lower. These variations may be attributed to both preharvest and postharvest factors, including horticultural practices, environmental conditions (e.g., temperature, relative humidity, and vapor pressure deficit [VPD]), as well as crop management, agrochemical inputs, and nutritional status, all of which influence daily photosynthetic activity [17]. Notably, the production areas in Prachin Buri, Uthai Thani, and Pala-U are influenced by forest-associated microclimates, which may buffer environmental fluctuations and contribute to more stable VPD conditions around the durian trees (**Figure 4**). VPD plays a critical role in regulating leaf transpiration and photosynthesis [29]. Under conditions of high temperature and low relative humidity, when VPD exceeds approximately 1.0 - 1.5 kPa, stomatal closure may occur, resulting in reduced photosynthesis and transpiration rates [30]. Therefore, durian production

areas influenced by forest-mediated microclimates that maintain more stable VPD conditions throughout the day may represent an important preharvest factor contributing to enhanced pulp dry matter at a given developmental stage.

As sulfur content, sulfur is an essential element for plant growth and metabolism. In durian pulp, sulfur availability influences nitrogen metabolism, altering the nitrogen-to-sulfur (N:S) ratio, which can affect fruit quality. Sulfur limitation has been reported to increase nitrate-N and free amino acid concentrations while reducing plant growth rate and soluble protein content [31]. Durian orchard commonly involve the use of potassium fertilizers with high sulfur content, such as potassium sulfate (0–0–50). In addition, sulfur is sometimes applied in the form of methionine-based fertilizers in commercial clones intended for export to the Chinese market. Sulfur is an essential nutrient for durian trees, contributing to yellow pulp coloration and supporting various metabolic processes in the fruit. In general, sulfur content in durian pulp is approximately 0.1%, which is considered sufficient to support normal durian growth and development [27]. However, excessive sulfur application may affect the formation of volatile esters and sulfur-containing compounds in the fruit [32]. Preharvest influence on sulfur content in durian fruit and its relationship to volatile sulfur-containing compounds were investigated. Sulfur present in unripe durian pulp serves as a substrate for amino acid synthesis and can be subsequently be transformed into thiol and sulfide compounds during ripening, as described in the Yang's cycle [33]. Our study indicates that preharvest factors, particularly the application of sulfur-containing fertilizers such as potassium sulfate (K_2SO_4), influence sulfur accumulation in unripe durian pulp [34]. Similarly, previous reports have shown that potassium chloride (KCl) and potassium sulfate (K_2SO_4) fertilizers can alter volatile compound profiles in potato tubers [32]. Therefore, elevated sulfur content in unripe durian pulp may affect methionine and ethionine levels, ultimately contributing to the formation of ethanethiol in ripe durian.

Table 3 Dry matter and sulfur content in unripe pulp, and color and sugar contents in ripe pulp from various sources of 'Monthong' durian.

Attributes	Source			
	Prachin Buri	**Uthai Thani**	**Rayong**	**Pala-U**
Unripe durian pulp				
Dry matter (%)	$36.85^{ab} \pm 1.50$	$39.69^{a} \pm 2.61$	$34.16^{c} \pm 0.48$	$37.95^{ab} \pm 0.16$
Sulfur content (%)	$0.065^{b} \pm 0.009$	$0.067^{b} \pm 0.009$	$0.153^{a} \pm 0.011$	$0.037^{c} \pm 0.004$
Ripe durian pulp				
L^*	$82.47^{a} \pm 1.56$	$81.01^{a} \pm 0.92$	$77.75^{b} \pm 0.47$	$78.89^{b} \pm 0.24$
a^*	$1.78^{b} \pm 0.71$	$2.32^{b} \pm 0.43$	$3.89^{a} \pm 0.48$	$2.23^{b} \pm 0.12$
b^{*ns}	38.95 ± 5.93	39.95 ± 3.09	42.88 ± 2.09	39.26 ± 0.42
C^{*ns}	39.00 ± 5.95	40.02 ± 3.11	43.05 ± 2.12	39.33 ± 0.42
h	$87.49^{a} \pm 0.69$	$86.74^{a} \pm 0.40$	$84.87^{b} \pm 0.41$	$86.66^{a} \pm 0.15$
Fructose (g kg^{-1})	$22.39^{ab} \pm 16.35$	$24.35^{b} \pm 3.16$	$28.06^{b} \pm 2.34$	$43.31^{a} \pm 6.10$
Glucose (g kg^{-1})	$132.77^{ab} \pm 30.50$	$117.02^{b} \pm 6.48$	$143.92^{a} \pm 10.10$	$137.71^{a} \pm 18.48$
Sucrose (g kg^{-1})	$136.00^{ab} \pm 22.17$	$154.56^{a} \pm 11.61$	$121.78^{b} \pm 3.60$	$156.01^{a} \pm 8.01$

Data are expressed as the mean values ± SD of three replicate assays, N.D. is not detected.

[a,b] letters indicate significant different ($p < 0.05$) values according to the Duncan's multiple range test (DMRT) in the same row.

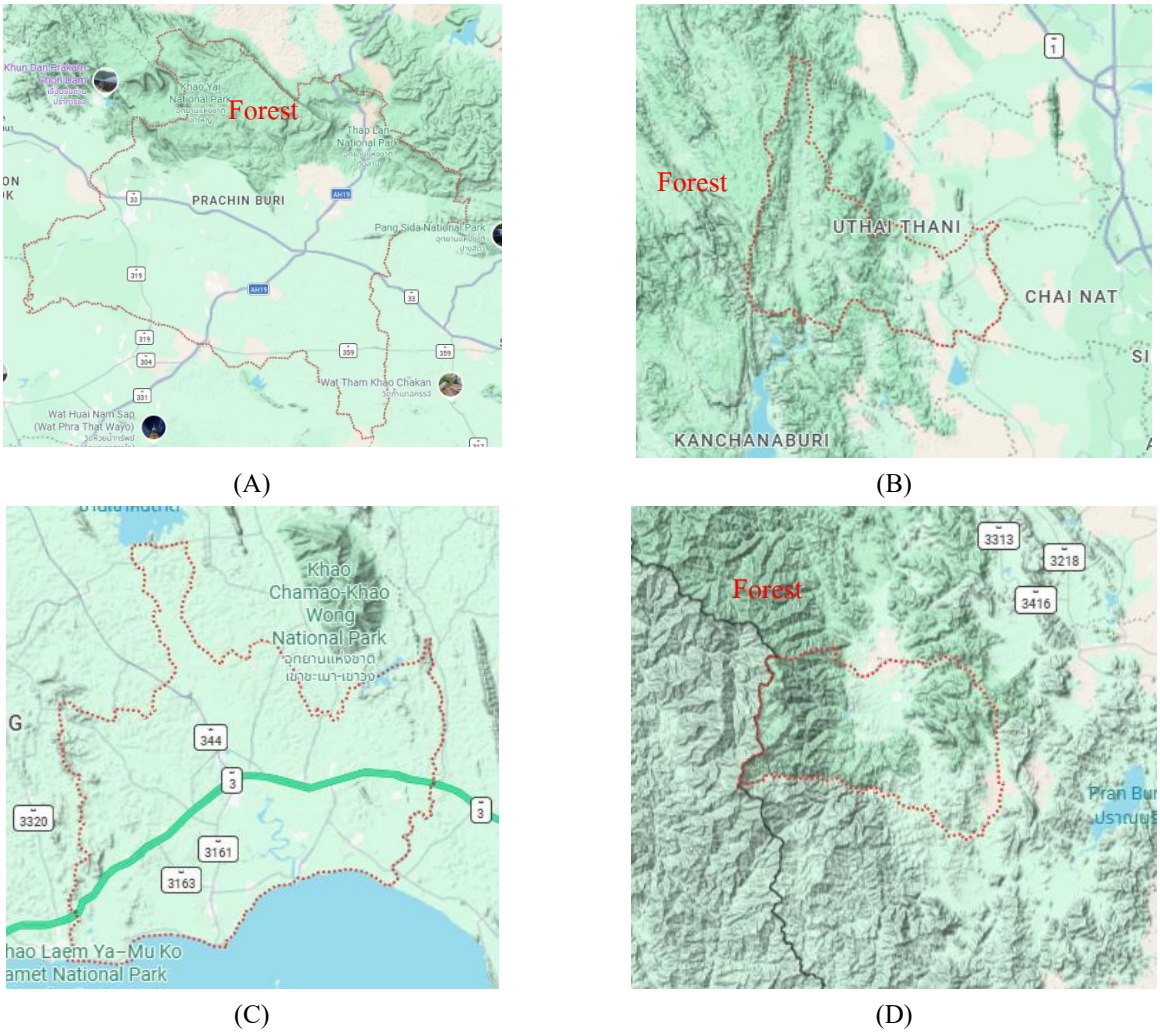


Figure 4 Geographical locations and the influence of forest-associated microclimates on the regulation of vapor pressure deficit (VPD) in 'Monthong' durian orchards from geographical indication areas: Prachin Buri (A), Uthai Thani (B), Rayong (C), and Pala-U (D).
Source: https://www.google.com/maps

Among the studied sources, Pala-U exhibited the lowest sulfur content, while Prachin Buri and Uthai Thani showed intermediate levels, with sulfur contents of 0.065 ± 0.009% and 0.067 ± 0.009% (w/w), respectively. Although these values appear to be negligible or statistically insignificant, it may still have practical significance with respect to the aroma threshold value for achieving a mild aroma. Durian from Rayong, which had the highest sulfur content in the pulp, exhibited greater pulp yellowness (b^* = 3.89 ± 0.48), whereas its hue angle was lower than that of the other sources. Although the differences in pulp color parameters were statistically significant, in the commercial market the practical range of pulp color typically falls within a $h°$ of 80 - 100, where visual differences are generally not perceived as significant (**Figure 3**) [2]. The differences in sulfur content among the four geographical sources may be partially attributed to variations in fertilization practices, particularly the application of potassium- and sulfur-containing fertilizers. As shown in **Table 1**, orchards in Prachin Buri and Uthai Thani applied N–P–K fertilizers with formulations of 15–5–20 and 15–5–25 (+7% sulfate) from fruit set to harvest. High potassium fertilization is known to promote carbohydrate accumulation and fruit sweetness, while sulfur plays an important role in the biosynthesis of sulfur-containing amino acids and volatile compounds that contribute to durian aroma. The application of the 15–5–25 (+7% sulfate) fertilizer may therefore have contributed to the relatively higher sulfur content observed in fruits from both regions. In Rayong, fertilization practices were more intensive and included

the application of 15–5–20, 15–5–25 (+7% sulfate), 0–0–60 (potassium chloride), and amino acid foliar sprays every 10 days from flowering until harvest. These additional nutrient inputs may have further enhanced sulfur accumulation and influenced the development of flavor-related metabolites. In contrast, the orchard in Pala-U reportedly did not apply fertilizers during fruit development. This observation is consistent with the significantly lower sulfur content detected in unripe pulp from Pala-U compared with the other regions.

Sugar analysis of the pulp showed that sources with higher DM content, Uthai Thani (39.69% DM), Pala-U (37.95% DM), and Prachin Buri (36.85% DM), also exhibited higher sucrose contents compared with Rayong. These results indicate a relationship between DM and starch content in the pulp. Starch is converted into non-reducing sugars, primarily sucrose, a process that occurs approximately one to two weeks before fruit maturity [1]. As reported in [26], sucrose, glucose, and fructose are major contributors to total soluble solids (SSC); however, SSC is not a reliable indicator of sweetness in durian pulp. Instead, individual sugar composition is more closely associated with perceived sweetness, with the reducing sugars glucose and fructose showing a stronger positive correlation with sweetness than sucrose.

Interestingly, in the present study, durian from Pala-U and Prachin Buri exhibited superior sensory taste, which corresponded with higher contents of reducing sugars (glucose and fructose). Therefore, the enzymatic conversion of sucrose to glucose and fructose during ripening represents an important area for future research, particularly for developing tailored strategies to optimize sweetness in durian fruit according to consumer preferences.

Volatile profiles in durian pulp

To our knowledge, this study represents the first report of volatile profiles in ripe flesh of ‘Monthong’ durian from Pala-U, Prachin Buri, and Uthai Thani. Among the four sources, ‘Monthong’ durian from Rayong exhibited the greatest diversity of volatile compounds, with a total of 28 major volatiles identified, comprising 23 esters, 2 sulfur-containing compounds, and 2 alcohols. Durian from Prachin Buri contained 9 esters, 2 sulfur-containing compounds, and 1 alcohol, while samples from Uthai Thani contained 16 esters, 1 sulfur-containing compound, and 1 alcohol. Pala-U durian exhibited the lowest number of volatiles, with 5 esters, 2 sulfur-containing compounds, and 2 alcohols detected (**Table 4**, **Table S1** and **Figure S1**).

To identify key volatile compounds contributing to durian aroma, odor activity values (OAVs) were calculated. Compounds with OAVs greater than 1 were considered to have a significant impact on overall flavor perception. As aroma threshold value (ATV) represents the minimum concentration at which a compound can be perceived by the human olfactory system [20,35,36]. Among the ester compounds, ethyl 2-methylbutanoate (E2MB) exhibited the highest OAV, reaching 82,369.9. This extremely high OAV is attributed to its very low aroma threshold value (ATV) of only 0.01 - 0.1 ppb, indicating that E2MB is a key ester with a strong impact on durian flavor. ‘Monthong’ durian from Rayong contained the highest concentration of E2MB (6.331 ± 2.160 $\mu g \cdot g^{-1}$), which corresponded to intense fruity and strong flavor characteristics in sensory evaluation. E2MB is typically associated with green, fruity aroma notes. [35,36]. Therefore, durian containing high levels of E2MB may be less acceptable to consumers due to its intense green fruity flavor. In contrast, durian with lower E2MB concentrations exhibits milder ester notes, resulting in a more balanced fruity aroma with reduced odor intensity, as observed in fruit from Prachin Buri, Uthai Thani, and Pala-U sources.

Although OAV can be used to represent the contribution of individual volatile compounds to the overall aroma profile of a food matrix, its values may be influenced by several factors, including the accuracy of volatile compound quantification, the selection of odor threshold values, unit consistency between concentration and threshold data, and the analytical methods employed. Variations in odor threshold values among different matrices, such as water, air, and food systems, can substantially affect OAV calculations. Furthermore, matrix effects, interactions among volatile compounds (e.g., synergistic and masking effects), and differences in human sensory perception may influence the actual aroma contribution of a compound beyond that predicted by OAV alone. Therefore, although OAV is a useful indicator for identifying key aroma-active compounds, its interpretation should be supported by appropriate analytical methodologies, reliable odor threshold references, and complementary sensory

evaluation. A clear example of the variability in OAV calculations can be observed for E2MB, one of the most important ester compounds contributing to durian aroma. As [35] determined the OAV of E2MB in Musang King durian using an absolute quantification approach and reported an exceptionally high OAV of 82,369.9. In contrast, [20] reported OAV values of 85.95 and 86.25 for E2MB in the Chanthaburi 1 and Monthong cultivars, respectively, based on semi-quantitative analysis using relative concentrations normalized to an internal standard. These substantial differences demonstrate that OAV values are highly dependent on the quantification approach, concentration units, odor threshold references, and analytical methodologies employed. Therefore, direct comparisons of OAV values among studies should be interpreted with caution, particularly when different quantification methods, analytical procedures, and odor threshold sources are used.

Table 4 Volatile compounds in Monthong durian pulp from various sources.

Volatile compound no.	Volatile compounds	OAV	TTV	ATV	Description	Relative concentration (μg Thiophene g^{-1} FW)*			
						Prachin Buri	Uthai Thani	Rayong	Pala-U
Alcohol									
1	Ethyl alcohol	n/a	n/a	8 - 900 ppb	Alcoholic, burning taste	4.300 ± 0.602	5.939 ±2.193	5.735 ± 2.146	5.834 ± 2.852
2	1-propanol	n/a	n/a	5.7 - 40 ppm	Alcoholic, fruity flavor	N.D.	N.D.	0.328 ± 0.127	N.D.
3	Isoamyl alcohol	<1	50 ppm	250 ppb - 4.1 ppm	Fruity, banana, ethereal, cognac	N.D.	N.D.	N.D.	0.074 ± 0.022
Sulfur containing compound									
1	Ethanethiol	480,000	n/a	High strength odor	sulfurous, fruity, cool menthol	0.014^{b} ± 0.005	0.006^{c}±0.001	0.085^{a} ± 0.003	0.012^{b} ± 0.003
2	Diethyl disulfide	4,180,425	1 ppm in water	High strength odor	ripe onion, gassy onion	0.0007^{b} ± 0.0001	N.D.	0.0035^{a} ± 0.0004	0.0031^{a} ± 0.0017
Ester compound									
1	Ethyl acetate	<1	100 ppm	5 ppb - 5 ppm	dry fruit, sweet	1.643^{b} ± 0.225	4.703^{a}±1.060	4.319^{a} ± 0.581	0.236^{c} ± 0.090
2	Methyl propanoate	n/a	n/a	100 ppb - 8.8 ppm	Fruity	N.D.	N.D.	0.418 ± 0.022	N.D.
3	Ethyl propanoate	<1	25 ppm	9 - 45 ppb	sweet, fruity, rum, pineapple	1.929^{b} ± 1.409	7.562^{a}±1.702	6.574^{a} ± 0.976	N.D.
4	Ethyl 2-methylpropanoate	n/a	12.5 ppm	0.01 - 1 ppb	Ethereal and fruity with a rum- and eggnog-like nuance	0.029^{c} ± 0.019	0.462^{b}±0.155	0.626^{a} ± 0.027	0.027^{c} ± 0.002
5	Methyl 2-methylbutanoate	173.6	7.5 ppm	0.92 - 4.4 ppb	Ethereal, green apple	N.D.	0.024^{b}±0.022	0.119^{a} ± 0.007	N.D.
6	Ethyl butanoate	23.0	20 ppm	0.1 - 18 ppb	pineapple, cognac	0.426^{b} ± 0.193	2.106^{a}±0.283	3.826^{a} ± 1.021	N.D.
7	Propyl propanoate	n/a	20 ppm	57 ppb	Sweet, lift, tropical green, fruity notes	0.239^{b} ± 0.183	0.326^{b}±0.349	1.991^{a} ± 0.696	N.D.
8	Ethyl 2-methylbutanoate	82,369.9	40 ppm	0.01 - 0.1 ppb	sharp sweet, green apple, green fruity	0.274^{c} ± 0.176	2.436^{b}±0.831	6.331^{a} ± 2.160	0.102^{c} ± 0.035
9	Propyl 2-methylpropanoate	n/a	5 – 15 ppm	0.086 - 0.43 ppb	Pineapple-like Sweet flavor	N.D.	N.D.	0.055 ± 0.011	N.D.
10	Propyl butanoate	n/a	20 ppm	0.8 - 124 ppb	Pineapple and apricot-like, sweet fruity	0.054^{c} ± 0.013	0.105^{b}±0.029	0.445^{a} ± 0.062	N.D.
11	Ethyl pentanoate	n/a	30 ppm	1.5 - 5 ppb	Fruity odor	N.D.	0.032^{b}±0.007	0.127^{a} ± 0.060	N.D.

Volatile compound no.	Volatile compounds	OAV	TTV	ATV	Description	Relative concentration (μg Thiophene g^{-1} FW)*			
						Prachin Buri	Uthai Thani	Rayong	Pala-U
12	Butyl propanoate	n/a	n/a	25 - 440 ppb	Faintly sweet odor and apricot-like taste	N.D.	N.D.	0.019 ± 0.001	N.D.
13	Methyl hexanoate	n/a	n/a	10 - 87 ppb	Ether-like odor reminiscent of pine apple	N.D.	0.066^{b} ± 0.004	0.204^{a} ± 0.077	N.D.
14	Ethyl 3-hydroxybutanoate	n/a	30 ppm	n/a	Green, fruity and winy	N.D.	0.086^{a} ± 0.013	0.065^{a} ± 0.019	0.011^{b} ± 0.010
15	Ethyl tiglate	n/a	n/a	65 ppb	Fruity, caramel odor	N.D.	N.D.	0.069 ± 0.026	N.D.
16	Propyl 2-methylbutanoate	n/a	n/a	n/a	Winey, fruity	N.D.	0.050^{b} ± 0.018	0.420^{a} ± 0.153	N.D.
17	Ethyl hexanoate	84.5	10 ppm	0.3 - 5 ppb	Fruity and waxy with a tropical nuance	0.505^{c} ± 0.207	4.169^{b} ± 0.533	8.377^{a} ± 1.798	N.D.
18	Propyl hexanoate	n/a	50 ppm	n/a	Pineapple, fruity, sweet, tropical, fresh green and juicy	N.D.	0.090^{b} ± 0.012	0.474^{a} ± 0.129	N.D.
19	Ethyl heptanoate	n/a	10 ppm	2 ppb	Fruity and waxy with a green winey	N.D.	0.037^{b} ± 0.003	0.119^{a} ± 0.038	N.D.
20	Methyl octanoate	<1	20 ppm	200 - 870 ppb	Green, fruity, waxy, aldehydic, citric and fatty	N.D.	N.D.	0.026 ± 0.007	N.D.
21	Ethyl octanoate	<1	5 ppm	5 - 92 ppb	Waxy, fatty, aldehydic, coconut, creamy and dairy-like	N.D.	0.813^{a} ± 0.135	0.631^{a} ± 1.093	0.054^{b} ± 0.019
22	Propyl octanoate	n/a	n/a	n/a	n/a	N.D.	N.D.	0.011 ± 0.019	N.D.
23	Ethyl decanoate	n/a	20 ppm	8 - 12 ppb	Sweet, waxy, fruity	0.017 ± 0.015	N.D.	0.086 ± 0.148	N.D.

N.D. Indicates as non-detected.

a,b letters indicate significant different ($p < 0.05$) values according to the least significant differences (DMRT) in the same row, ns is no significant difference.

*The results were expressed as peak area/internal standard (IS) area×concentration of external standard (ES: thiophene) followed [26]. Description odor, aromatic threshold values (ATV), and taste threshold values (TTV) followed [36].

Description odor activity value (OAV) followed [35].

Figure 5 illustrates that E2MB, a primary volatile compound in durian, is derived from 2-methylbutanoyl-CoA through isoleucine metabolism [10,20,37]. Therefore, higher isoleucine availability can result in increased E2MB concentrations in durian pulp. The amino acid isoleucine is closely related to sulfur (S) availability, as sulfur nutrition significantly influences isoleucine content in plants. Specifically, sulfur deficiency reduces isoleucine levels in the free amino acid pool, whereas adequate sulfur supply helps maintain or increase isoleucine content, contributing to balanced plant nutrition and growth [31]. Consequently, 'Monthong' durian from Rayong, which exhibited higher sulfur content, showed not only increased sulfur-containing compounds in the pulp but also elevated ester production, particularly E2MB, with increasing sulfur levels. Among volatile sulfur-containing compounds (VSCs), Rayong durian had the highest concentration of ethanethiol, with OAV of approximately 480,000 indicating an extremely strong sulfurous odor. As shown in **Figure 5**, ethanethiol biosynthesis originates from sulfur-containing amino acids, including cysteine, methionine, and ethionine, which can be converted into methanethiol and ethanethiol and subsequently oxidized

into sulfur compounds, particularly diethyl disulfide [9,13-15,38,39]. Although diethyl disulfide was detected in three sources (Prachin Buri, Rayong, and Pala-U) at concentrations ranging from 0.0007 to 0.0035 ppm, these levels are well below the taste threshold value (TTV) of 1 ppm and are therefore unlikely to be perceptible.

VSCs are primarily derived from amino acid-related metabolic pathways and play a crucial role in the ethylene-mediated ripening process of durian. During ripening, serine serves as a precursor for cysteine biosynthesis, which subsequently contributes to the formation of glutathione (GSH). Glutathione can then be metabolized to produce hydrogen sulfide. Methionine is another important precursor, as it is converted to methanethiol through the action of methionine γ-lyase (MGL), followed by oxidation to various volatile sulfur compounds. In addition, methionine is converted to S-adenosylmethionine (SAM), which is subsequently metabolized to 1-aminocyclopropane-1-carboxylic acid (ACC), the immediate precursor of ethylene biosynthesis [12,13,33]. Ethionine has also been reported as a precursor of ethanethiol in durian pulp [9,14]. VSCs are key contributors to the characteristic aroma of durian and are closely associated with fruit ripening and postharvest physiological changes [15]. The concentrations of sulfur-containing volatiles generally increase during storage, reflecting the progression of biochemical and metabolic processes associated with ripening and senescence [2,26]. Major sulfur-containing volatile compounds identified in durian include hydrogen sulfide, which imparts a rotten egg-like odor; methanethiol, characterized by a rotten cabbage-like odor; and ethanethiol, which contributes onion-like and rubbery aroma notes [7,15]. These compounds, together with other sulfur-containing volatiles, are responsible for the distinctive and highly recognizable aroma profile of ripe durian fruit.

Monthong' durian from Pala-U was perceived as having a pleasant fruity aroma with minimal sulfur odor, as well as a creamy, rich, full-bodied, and complex taste. Notably, Pala-U durian contained only five ester compounds (ethyl acetate, ethyl 2-methylpropanoate, ethyl 2-methylbutanoate, ethyl 3-hydroxybutanoate, and ethyl octanoate) present at relatively low concentrations of 0.236 ± 0.090 $\mu g \cdot g^{-1}$, 0.027 ± 0.002 $\mu g \cdot g^{-1}$, 0.102 ± 0.035 $\mu g \cdot g^{-1}$, 0.011 ± 0.010 $\mu g \cdot g^{-1}$, and 0.054 ± 0.019 $\mu g \cdot g^{-1}$, respectively. Interestingly, isoamyl alcohol was detected exclusively in Pala-U durian at 0.074 ± 0.022 $\mu g \cdot g^{-1}$. Isoamyl alcohol, which imparts fruity and banana-like notes, can be biosynthesized from L-leucine and serves as a key precursor for isoamyl acetate, an important volatile in banana and other fruits [33,40,41]. The formation of mild ester-related flavors, together with lower concentrations of sulfur compounds, which contribute to the complex and full-bodied sensory profile of Pala-U 'Monthong' durian, may be associated with L-leucine present in the pulp. L-Leucine serves as a precursor for the biosynthesis of isoamyl alcohol and isoamyl acetate, key volatile aroma compounds responsible for banana-like sensory characteristics [42]. Further studies are planned to investigate the effects of planting location and abiotic stress on leucine accumulation in durian fruit.

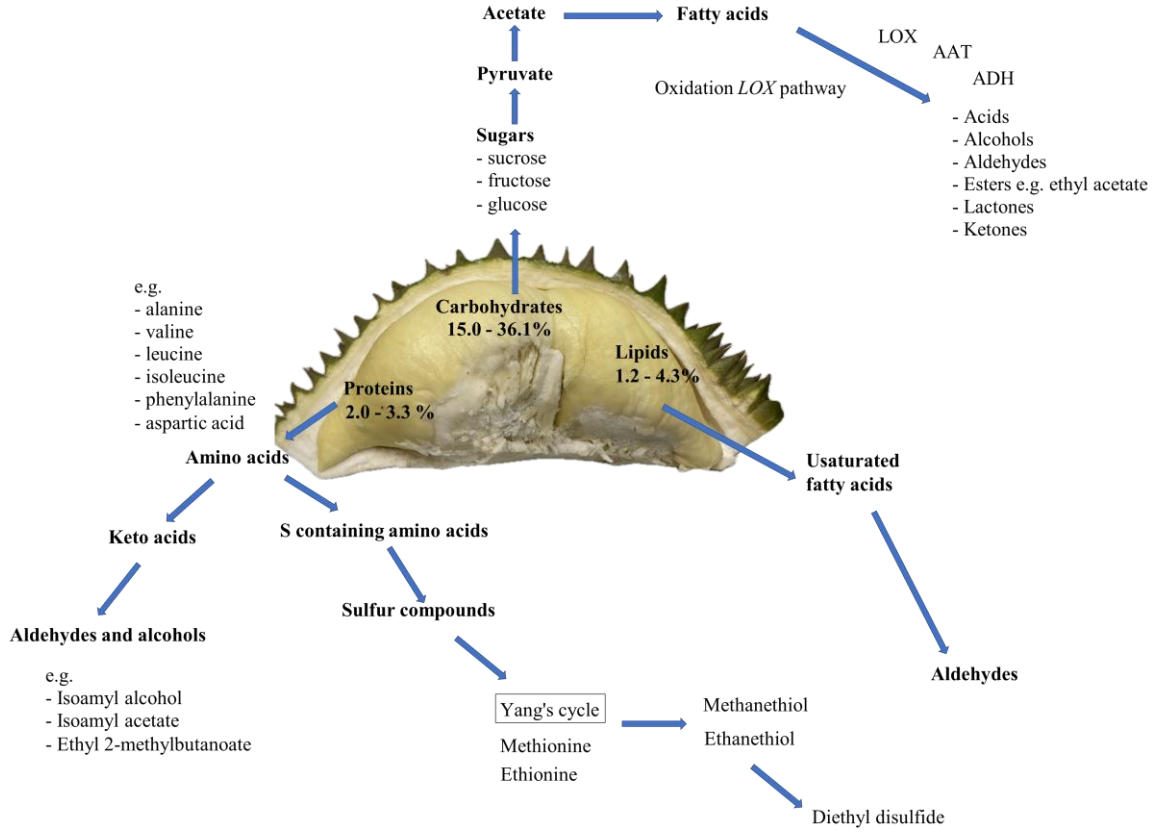


Figure 5 Schematic summary of the biosynthetic pathways leading to the formation of major volatile compounds in durian pulp. Abbreviations: LOX, lipoxygenase; AAT, alcohol acyltransferase; ADH, alcohol dehydrogenase. Adapted from [1,9,10,38].

Sensory evaluation

Using a panel of experienced assessors with extensive expertise in evaluating 'Monthong' durian pulp from major production regions in Thailand, sensory evaluation was conducted to examine differences in eating quality among four GI 'Monthong' durian sources. The assessed sensory attributes included appearance, fruity-like odor, sulfur-like odor, creaminess, and umami taste, with results presented in **Figures 6(A) - 6(D)**. Quantitative descriptive analysis (QDA) indicated that samples from Uthai Thani and Pala-U received higher appearance scores, consistent with their higher L* and hue angle ($h°$) values. Notably, $h°$ values approaching 90° indicate greater yellowness of the pulp (**Table 3**). For fruity-like odor, all sources showed high acceptance, supported by the presence of key ester compounds, particularly ethyl 2-methylbutanoate (E2MB), which exhibited high OAV, along with other ester compounds (**Table 4**). These observations are further supported by the relatively high DM and total sugar contents across all samples, which contribute to ester formation. In terms of sulfur-like odor, Rayong exhibited the highest intensity, corresponding to elevated levels of ethanethiol and diethyl disulfide in the pulp (**Table 4**). This may be associated with higher sulfur content in unripe pulp, which serves as a precursor for sulfur-containing amino acids and volatile compounds. Regarding creaminess, samples from Prachin Buri and Pala-U showed higher scores than those from Uthai Thani and Rayong. For umami taste, Pala-U exhibited the highest intensity, followed by Prachin Buri, which is consistent with PCA results showing these two regions clustering together based on overall aroma characteristics. Previous studies have reported that 'Monthong' durian typically scores high in sweetness but relatively low in creaminess, potentially due to firmer texture [19]. However, fruit quality is strongly influenced by preharvest factors, although agricultural practices may have a lesser impact on metabolic profiles compared to cultivar and harvest year [13]. In GI regions, differences in fatty acid composition have also been reported and can be used to

differentiate the origin of 'Monthong' durian, suggesting that production location plays a significant role in determining fruit flavor and sensory characteristics [18].

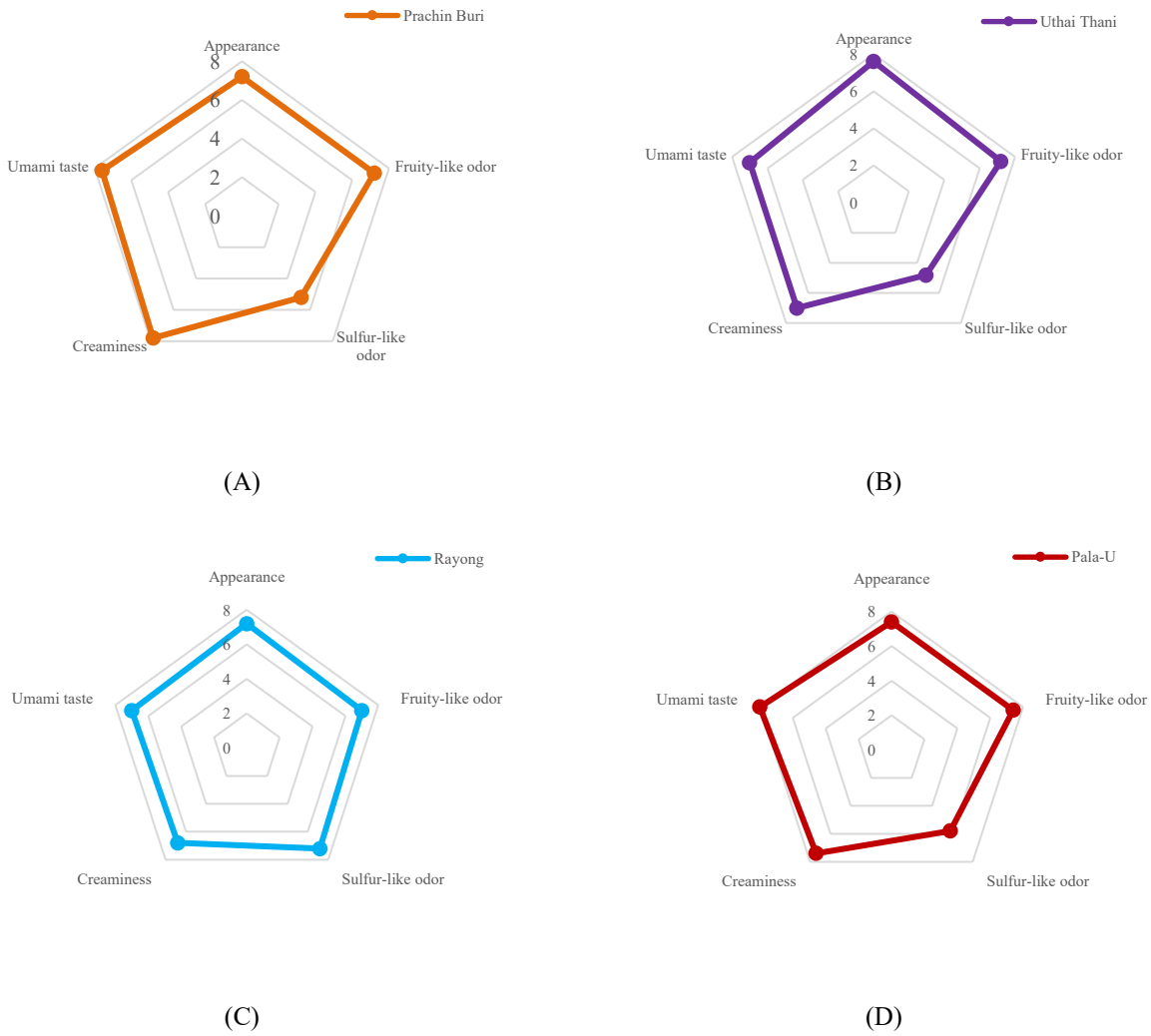


Figure 6 Sensory profile of 9-sensory attributes in 4 geographical area Monthong durian; Prachin Buri (A), Uthai Thani (B), Rayong (C), Pala-U (D).

The relationship of durian source on aroma volatiles

Figure 7 illustrate a PCA score plot combined with K-means clustering based on 28 volatile compounds in durian pulp (3 alcohols, 2 sulfides, and 23 esters), illustrating the separation of samples according to geographical origin. The PCA explained 70.5% of the total variance, with PC1 and PC2 accounting for 51.5% and 19.0%, respectively. Samples were clearly separated by origin. K-means clustering further classified the samples into three distinct clusters: Pala-U and Prachin Buri were grouped together, while Uthai Thani and Rayong formed separate clusters, indicating notable differences in volatile profiles. As in **Figure 8** presents the PCA biplot showing the relationships between volatile compounds and sample origins. PC1 and PC2 accounting for 51.5% and 19.0%, respectively. The PCA biplot clearly separated durian samples according to geographical origin. Rayong samples were associated with sulfur-related compounds and aroma attributes, including ethanethiol (0.150, 0.268), diethyl disulfide (−0.013, 0.365), sulfur content (0.190, 0.093), and sulfur-like odor (0.097, 0.328), indicating a stronger contribution of sulfur volatiles to the characteristic durian aroma. Uthai Thani samples were characterized by a group of ester compounds, such as ethyl acetate

(0.195, –0.175), ethyl butanoate (0.190, –0.162), ethyl hexanoate (0.188, –0.158), and propyl butanoate (0.195, –0.138), which are commonly associated with fruity aroma notes (–0.108, –0.029). In contrast, Pala-U samples were positively associated with fructose (–0.062, 0.191), umami taste (–0.186, 0.145), and 3-methyl-1-butanol (–0.166, 0.175), whereas Prachin Buri samples were more closely related to sucrose (–0.157, –0.179), appearance, and several minor ester compounds. These results suggest that differences in volatile composition and sensory characteristics among geographical indication regions contributed substantially to the observed sample discrimination [19]. In our present study, durian from Rayong also exhibited significantly higher concentrations of propyl butanoate, propyl hexanoate, and ethyl 2-methylbutanoate in the pulp compared to other production areas. Interestingly, although durian from Rayong showed the lowest dry matter (DM) content, which is typically associated with reduced starch and sucrose levels, glucose content tended to be higher than in other sources. This may contribute to the elevated levels of volatile esters, potentially through enhanced oxidative pathways, including the lipoxygenase (LOX) pathway. Additionally, the relatively high sulfur content may influence the distribution and accumulation of ester compounds in Rayong durian. A possible mechanism by which sulfur influences ester biosynthesis involves its role in sulfur-containing amino acids, particularly methionine, which is a key precursor in ethylene biosynthesis. Sulfur may also enhance the expression of alcohol acyltransferase (AAT) and lipoxygenase (LOX), enzymes directly involved in ester formation. Furthermore, ethylene is known to regulate LOX pathway activity, thereby promoting ester production during fruit ripening. Collectively, these interactions suggest that sulfur may indirectly enhance ester accumulation in ripe durian by modulating ethylene biosynthesis and the expression of key enzymes in ester biosynthetic pathways [43]. In **Figure 9** represent Hierarchical clustering analysis revealed two major sample groups. Pala-U and Prachin Buri were clustered together, indicating relatively similar chemical and sensory profiles, whereas Rayong and Uthai Thani formed a separate cluster characterized by higher abundances of volatile compounds. Rayong samples exhibited the highest levels of sulfur-related compounds, including ethanethiol, diethyl disulfide, sulfur content, and sulfur-like odor, suggesting a stronger contribution of sulfur volatiles to the characteristic durian aroma. In contrast, Uthai Thani samples were associated with elevated concentrations of fruity ester compounds, such as ethyl acetate, ethyl butanoate, and ethyl hexanoate. Pala-U samples showed higher levels of fructose, 3-methyl-1-butanol, umami taste, and fruity-like odor, indicating a greater contribution of taste-related attributes. These findings demonstrate that geographical origin significantly influenced both volatile composition and sensory characteristics of Monthong durian.

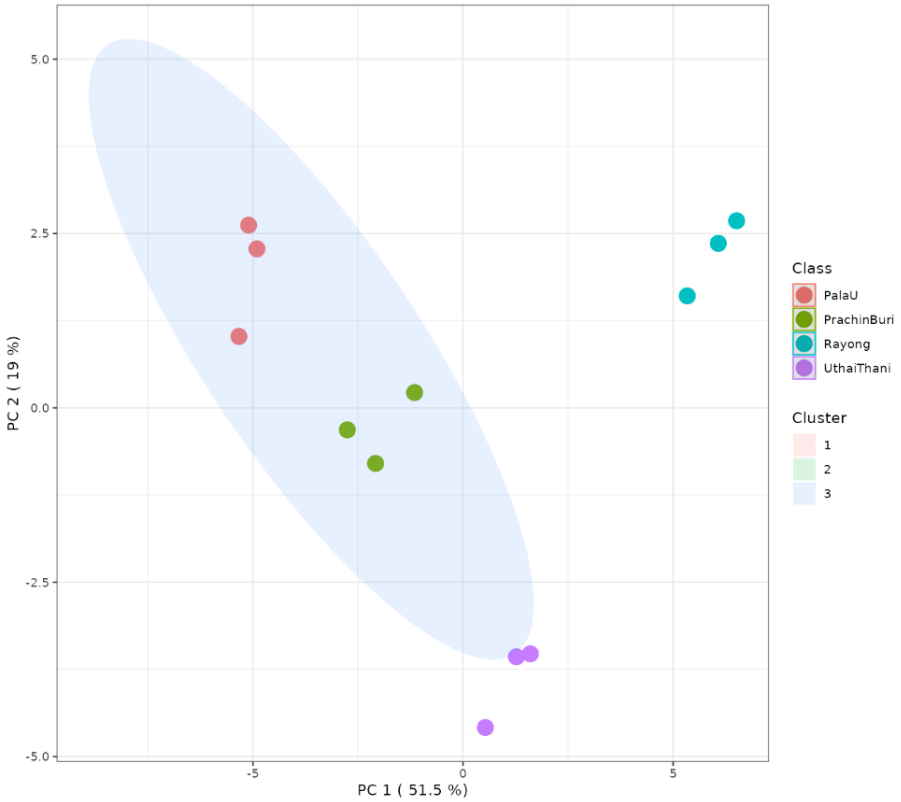


Figure 7 PCA score plot combined with K-means clustering based on 29 volatile compounds in durian pulp (3 alcohols, 2 sulfides, and 23 esters), showing the separation of samples according to geographical origin.

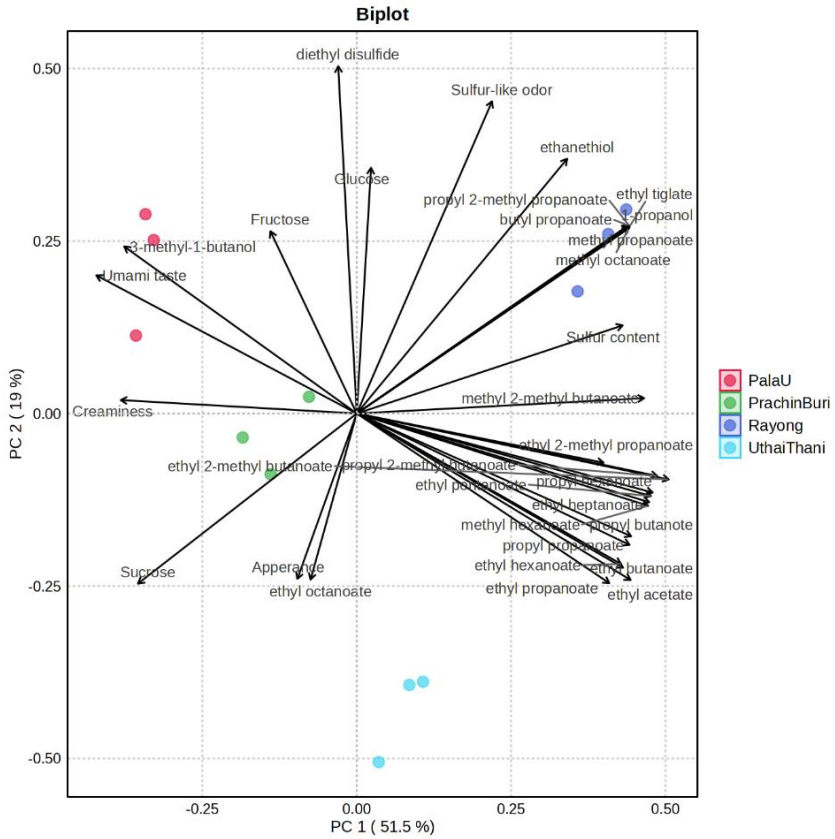


Figure 8 PCA biplot showing the relationships between 29 volatile compounds in durian pulp (3 alcohols, 2 sulfides, and 23 esters) and sample origins.

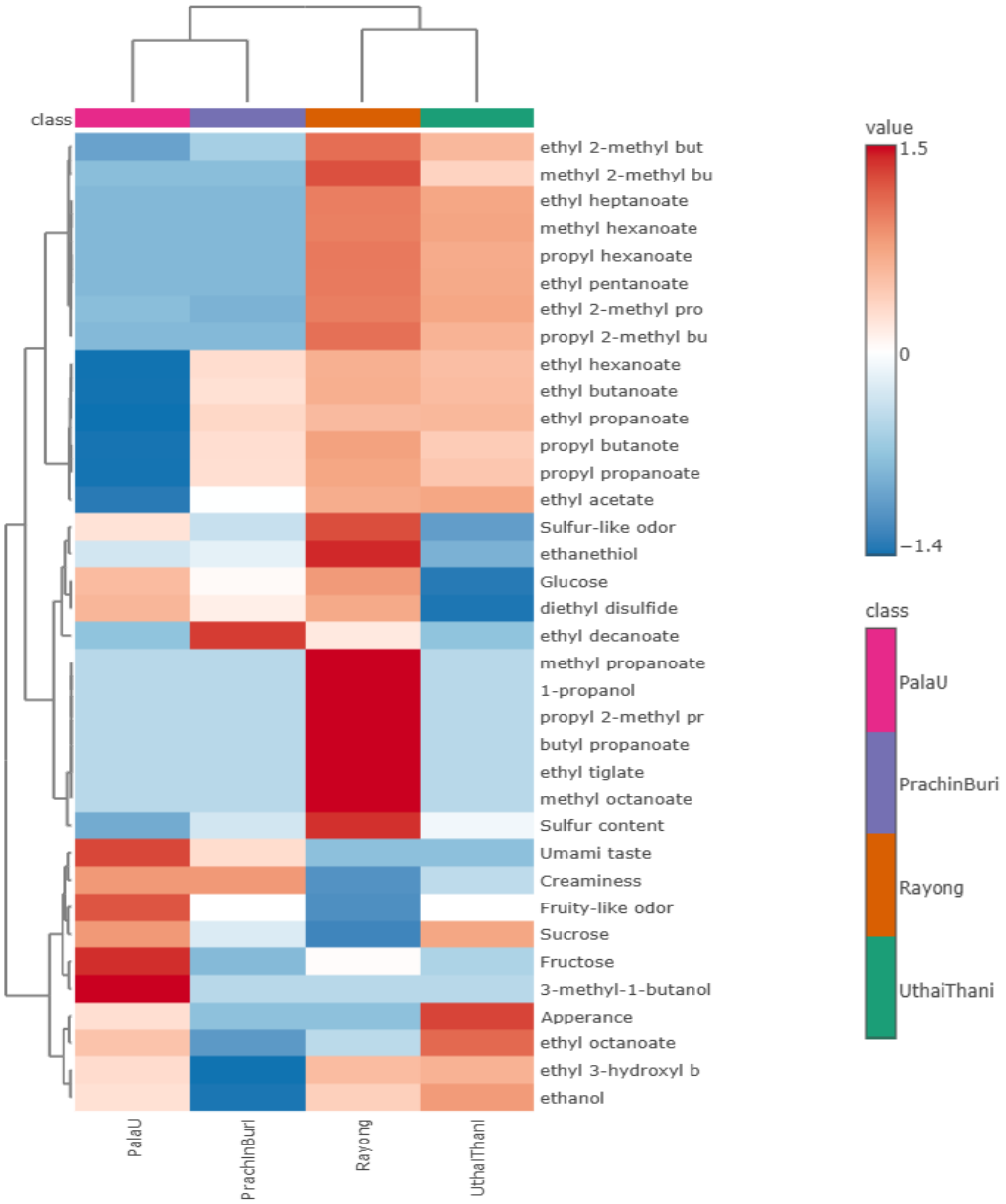


Figure 9 Heatmaps of normalized GC-MS data of volatile profiling, sensory evaluations and sugars analysis of 'Monthong' durian samples according to geographical origin.

Conclusions

Monthong' durian quality is strongly influenced by preharvest factors, particularly sulfur content and dry matter (DM). High sulfur levels are associated with increased volatile sulfur and ester compounds, resulting in a stronger aroma, whereas lower sulfur content (<0.1% DW) contributes to a milder, more complex flavor profile. GI areas with forest-associated microclimates tend to enhance DM, while variations in sulfur and sugar composition shape aroma and taste. Sensory and PCA results confirm that volatile profiles differentiate GI origins. These findings support optimizing preharvest management, especially sulfur balance, to produce premium 'Monthong' durian with desirable mild and complex flavor characteristics. In future studies should incorporate long-term data collection over a 5 - 10 years period, together with more comprehensive monitoring of orchard-level microclimatic conditions throughout fruit development, from flowering to harvest. Such long-term datasets

would provide a robust foundation for advanced investigations and facilitate a deeper understanding of the factors influencing durian aroma quality and volatile compound formation. Furthermore, future research should evaluate the effects of amino acid-related fertilization strategies, particularly those involving leucine and isoleucine, using various application methods, and investigate their relationships with the biosynthesis and accumulation of volatile aroma compounds associated with these amino acid precursors.

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Declaration of generative AI in scientific writing

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CRediT author statement

Piyapong Sonkaew: Conceptualization; Writing - Original Draft; Investigation; Visualization. **Anuyut Thadapitakporn**: Writing - Reviewing and Editing. **Vorapat Vachirayagorn**: Writing - Reviewing and Editing. **Supoj Pratheepthinthong**: Writing - Reviewing and Editing. **Ubonrat Siripatrawan**: Writing - Reviewing and Editing; Supervision. **Amporn Sane**: Writing - Reviewing and Editing. **Panuwat Suppakul**: Conceptualization; Writing - Reviewing and Editing; Supervision; Project administration.

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Supplementary Data

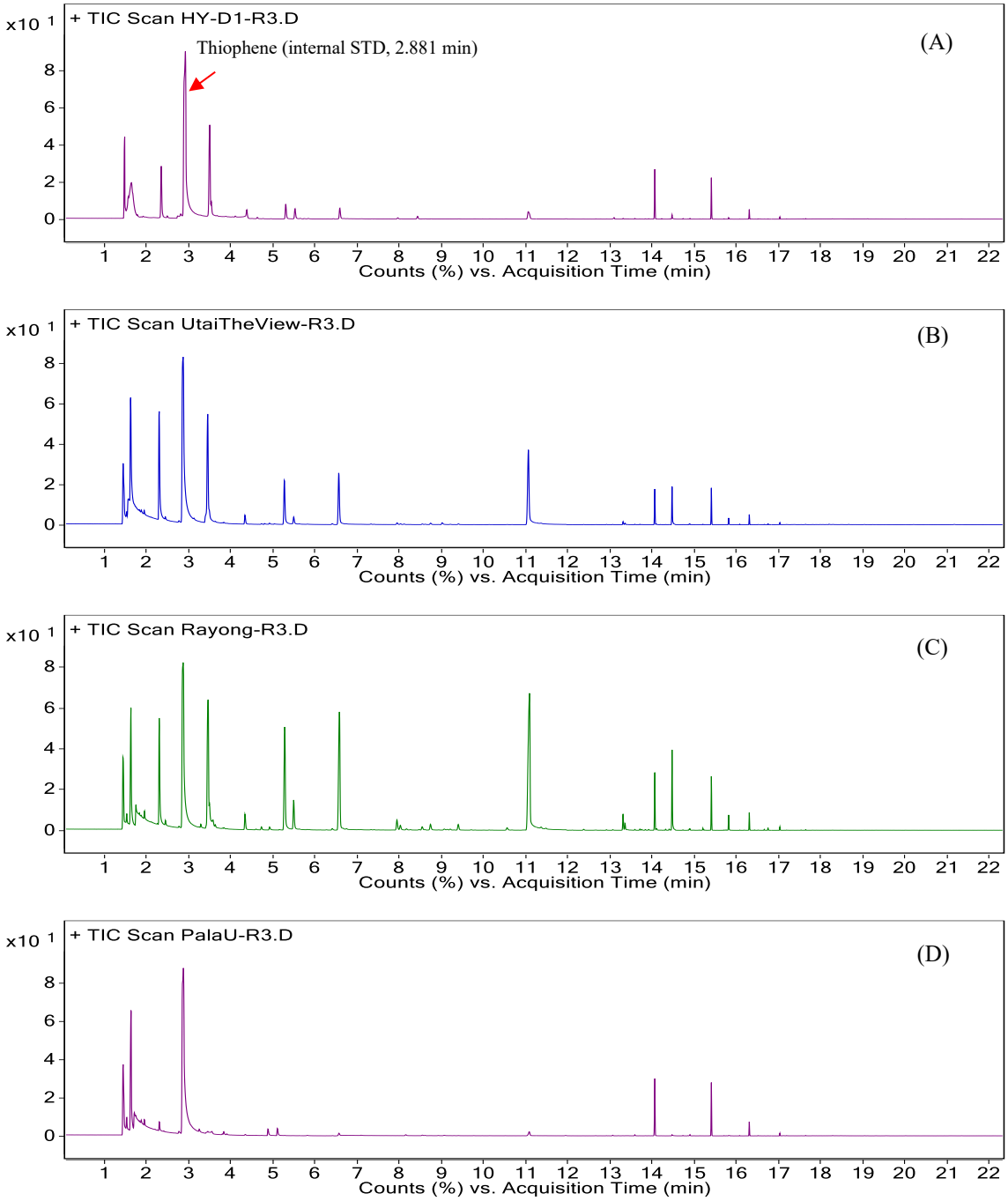


Figure S1 GC–MS chromatograms of volatile compounds identified in 'Monthong' durian pulp from different geographical sources: Prachin Buri (A), Uthai Thani (B), Rayong (C), and Pala-U (D).

Table S1 Retention time (RT), experimentally determined retention index (RI) on the HP-5MS column, literature RI values on the DB-5 column, and CAS numbers of volatile compounds identified in 'Monthong' durian pulp from different geographical sources.

No	Compounds	RT (min)	RI[a]	Ri[b]	CAS
Alcohol					
1	ethyl alcohol	1.637	<700	n/a	64-17-5
2	1-propanol	1.959	<700	n/a	71-23-8
3	Isoamyl alcohol	3.841	772	720[b]	123-51-3
Sulfur containing compound					
1	ethanethiol	1.746	<700	<600[b]	75-08-1
2	diethyl disulfide	8.614	966	907[b]	110-81-6
Ester compound					
1	ethyl acetate	2.308	<700	<600[b]	141-78-6
2	methyl propanoate	2.455	<700	n/a	554-12-1
3	ethyl propanoate	3.470	727	688[b]	105-37-3
4	ethyl 2-methylpropanoate	4.343	791	741[b]	97-62-1
5	methyl 2-methyl butanoate	4.736	782	759[b]	868-57-5
6	ethyl butanoate	6.416	820	787[b]	105-54-4
7	propyl propanoate	5.499	829	n/a	106-36-5
8	ethyl 2-methyl butanoate	6.585	871	833[b]	7452-79-1
9	propyl 2-methylpropanoate	6.749	899	n/a	644-49-5
10	propyl butanoate	7.949	917	n/a	105-66-8
11	ethyl pentanoate	8.031	947	n/a	539-82-2
12	butyl propanoate	8.271	955	n/a	590-01-2
13	methyl hexanoate	8.745	970	903[b]	106-70-7
14	ethyl 3-hydroxybutanoate	9.062	980	n/a	5405-41-4
15	ethyl tiglate	9.214	984	n/a	5837-78-5
16	propyl 2-methylbutanoate	9.405	990	929[b]	37064-20-3
17	ethyl hexanoate	11.097	1047	981[b]	123-66-0
18	propyl hexanoate	13.317	1119	n/a	626-77-7
19	ethyl heptanoate	13.361	1121	n/a	106-30-9
20	methyl octanoate	13.715	1134	n/a	111-11-5
21	ethyl octanoate	14.479	1160	1198[b]	106-32-1
22	propyl octanate	15.210	1184	n/a	624-13-5
23	ethyl decanoate	15.821	1204	1380[b]	110-38-3

[a]Retention index of compounds on the HP5-MS

[b]Retention index of compounds on the DB-5 [35]